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14. ABSTRACT

The goal of this effort is to produce the largest monolithic telescope capable of being lifted by a Delta IV or Atlas V EELV to 500 km. A strategy using a 4 m borosilicate mirror is proposed. A preliminary architecture was identified with a new mirror design that is estimated to be 40 times stiffer than a meniscus mirror of the same mass. A mass budget and conceptual packaging details were completed. The mirror was evaluated for its ability to handle launch loads using a time based strength, flaw size, and estimated support stresses. A thermal figuring method was investigated as the wavefront correction system with power and performance estimates. Future efforts will demonstrate mirror casting and thermal figuring.

15. SUBJECT TERMS

Borosilicate, E6, monolithic, mirror, space telescope, architecture, mass budget, thermal figuring, coefficient of thermal expansion, casting, support stresses, flaw size, strength

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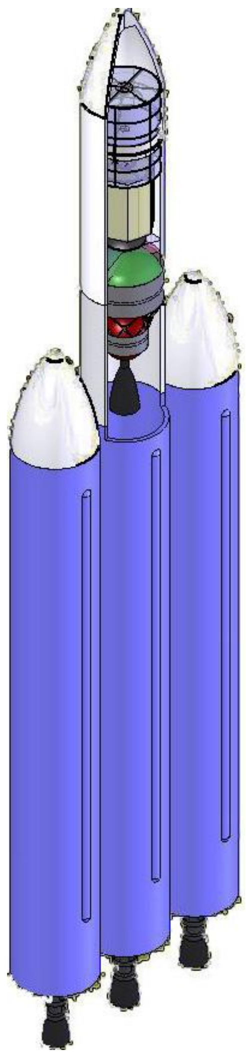


A space imaging concept based on a 4m spun-cast borosilicate monolithic primary mirror
(June 2010)

Steve West, S.H. (Hop) Bailey, Steve Bauman

Brian Cuerden, Blain Olbert

(University of Arizona, Steward Observatory)

and

Ray Bell and Zac Granger (Lockheed Martin)

Delta IV Heavy

Atlas V 552

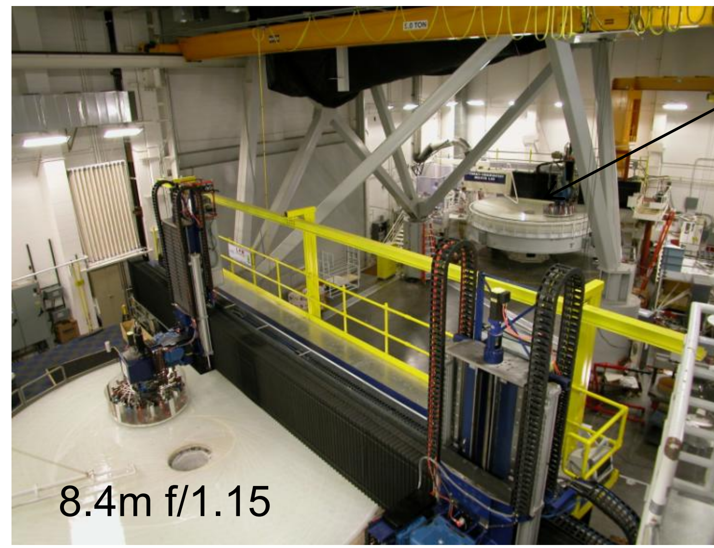
Goals

- Create the largest monolith capable of being lifted in a DELTA VI or ATLAS V EELV to 500km LEO.
- Utilize existing technology for simplicity and rapid development.
- Use monolithic technology already demonstrated to be scalable to Ares V fairing sizes whose manufacturing is currently active.
- Aim for complexity and areal density between HST and JWST.
- Support a notional surveillance mission with a very large multi-band push-broom instrument and heritage spacecraft for demonstration.
- Provide wavefront control that rarely interrupts mission
- Continuous NIIRS 7+ imaging
- Stiff primary mirror supports 1g pre-flight testing with e.g., the LOTIS 6.5m Collimator.
- Assess feasibility of using a cast borosilicate primary mirror in space.

University of Arizona, Steward Observatory Capabilities

- **Devoted more than 25 years to casting, polishing, and testing very large, fast (~f/1.2) aspheric borosilicate honeycomb primary mirrors.**

Spinning furnace casts up to 8.4m mirrors as fast as f/1.1.



Highly aspheric mirrors are polished and tested after casting

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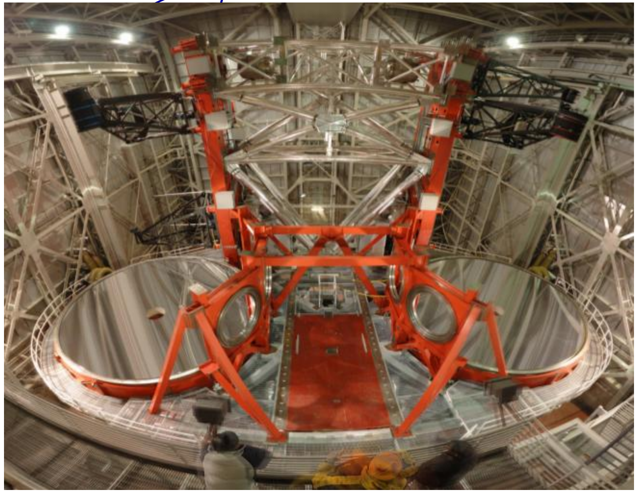
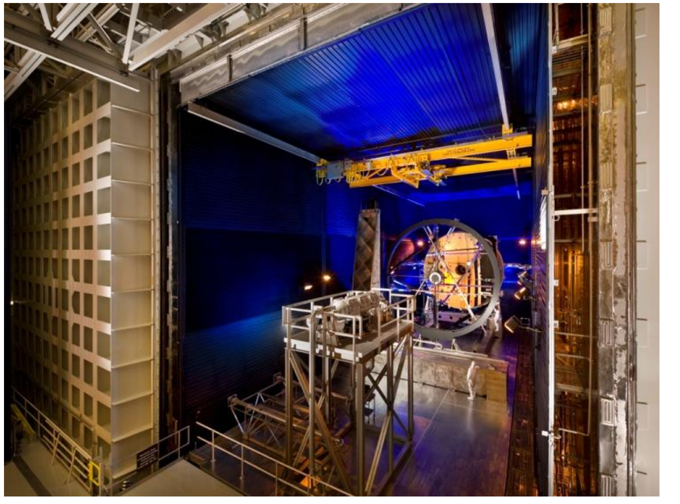
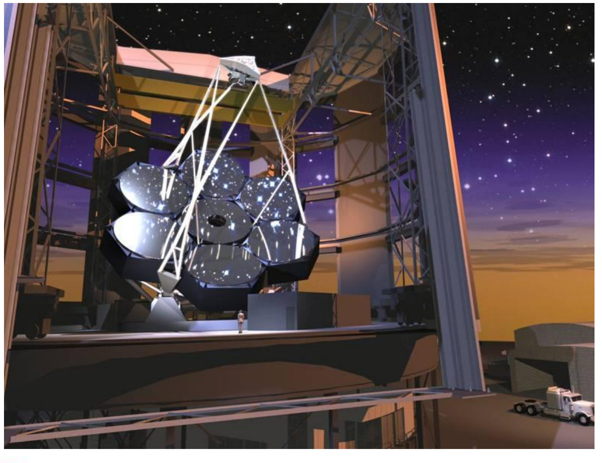
Projects with large borosilicate mirrors



LBT: 2-8.4m mirrors



LOTIS 6.5m Collimator
+ 4 other 6.5m Telescope facilities



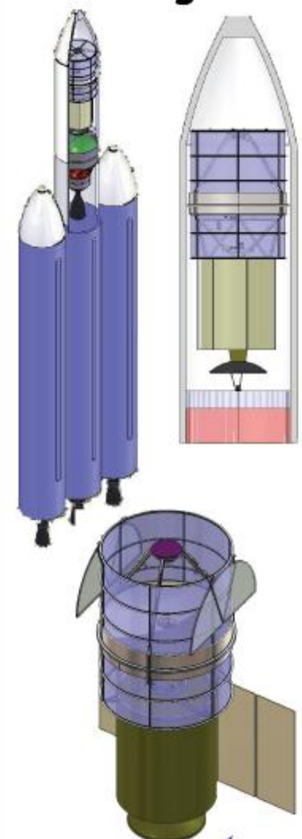
GMT: 7-8.4m mirrors are part of a 25m f/0.7 parent.
The first off-axis segment is cast and polishing is 80% completed.

4m Concept

Reference Mission

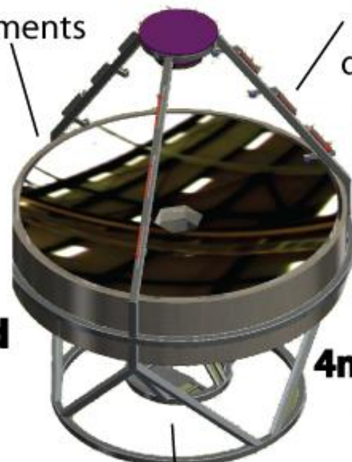
NIIRS 7+ minimum performance with a goal of NIIRS 8
500km circular orbit
Simultaneous MWIR and visible TMA push broom
Metric imaging wavelength 600nm
Resolution more important than light gathering power
(therefore a large central obstruction is acceptable)

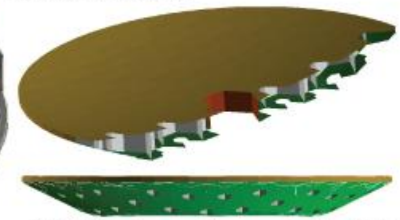
Packaged into existing Delta IV fairing



500 km circular orbit

Replace optical complexity with simplicity by flying a downsized, light-weighted version of UASO ground-based telescope





4m f/1.2 structured, light-weighted Monolithic Primary Mirror

THE UNIVERSITY OF ARIZONA.

Optical & Detector Requirements	8µm pixels, 2 pixels per Airy disk, consider 2.5 pixels per Airy disk during Study 1.2° FOV, conduct a trade during Study Field distortion less than 1/4 pixel across 64 pixels (1/8 Airy disk)

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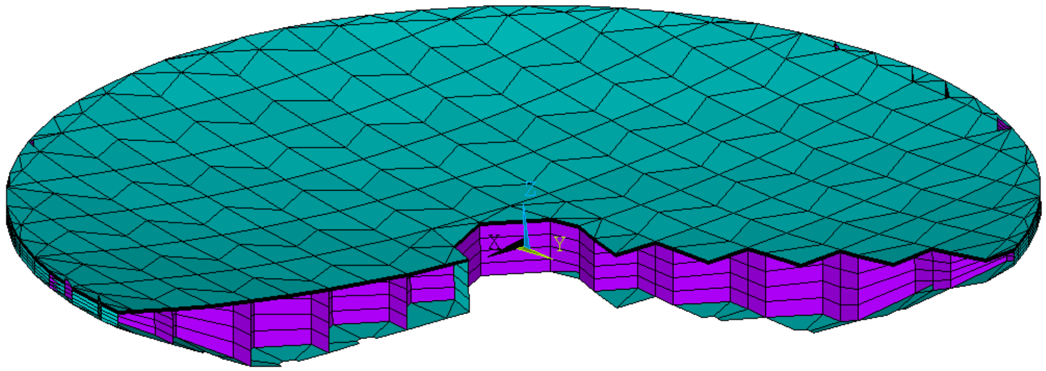
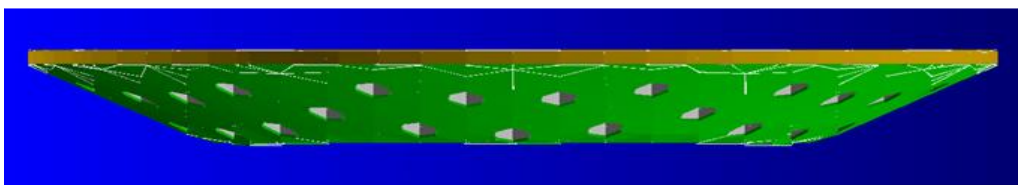
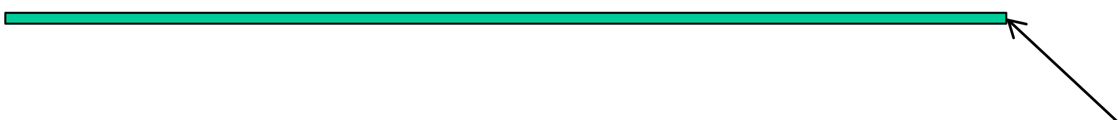
Proposed high efficiency 4m casting for space







Specifications:

- 4m f/1.2
- Weight: 1188 kg
- Areal density: 95 kg/m^2
- face/back plates: 12.7mm
- webs: 9.5mm thick
- 87 cells: 400mm diameter
- Contoured backplate
  - Stiffness x40 of equiv mass meniscus

Equivalent mass slab (1:100)
40mm thick

The above new type of casting is considered very low risk using heritage casting techniques, but is 1/7th the areal density of the mirrors previously cast by UASO.

Primary Mirror Comparison

Property	HST	Spitzer	JWST	UASO Flight qualified	Meniscus for flight+	UASO ground	Hextek Gas Fusion
Material	ULE	Be	Be	Ohara E6	ULE or Zerodur	Ohara E6	Borofloat
Diameter (m)	2.4	0.85	1.5 (seg)	4.0	4.0	8.4	Up to 1.5m
Temperature (K)	300	4	30	300	?	300	30 & 300
Surface figure (nm rms)	6.4	75	25	18†	15 (typ)	18 (typ)	?
Areal Density (kg/m^2)	180‡	28	26	95†‡	220‡*	700	50‡
Areal Cost (\$M/m^2) (adjusted to 2008 dollars)	21	13	6	3†	?	0.4	?

† Estimates to be refined with future work.

* Meniscus (1:40).

‡ includes substrate only.

Comparison of finished primary mirror optics. We estimate the cost of a finished flight-qualified 4m UASO mirror to be approximately 6-7 times the areal cost of a typical UASO mirror produced for ground-based telescopes. The added cost includes refined flaw detection and removal, enhanced treatments of as-cast surfaces, new mold designs, and dynamic and thermal TRL demonstrations. All areal costs adjusted to 2008.

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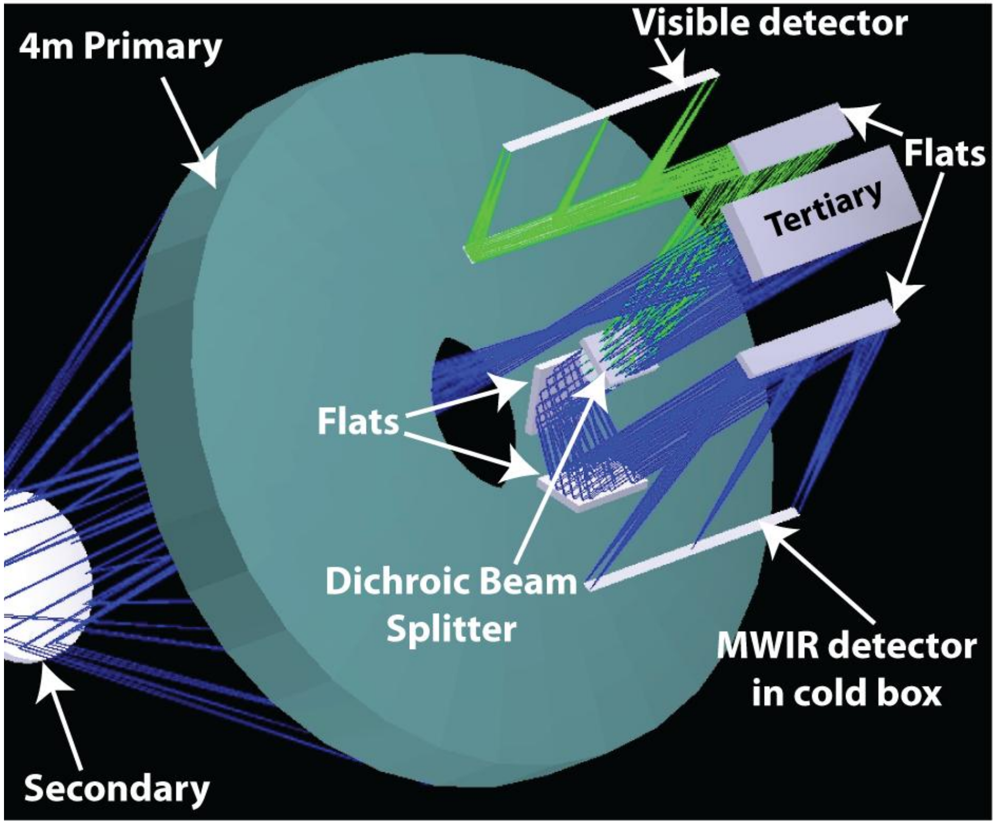
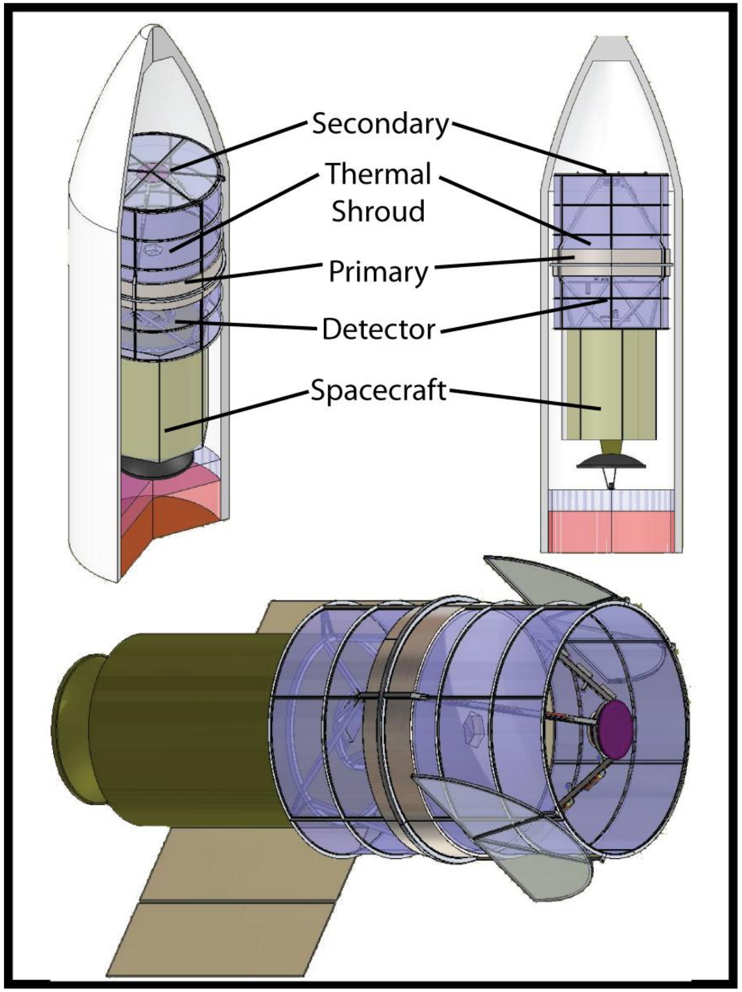
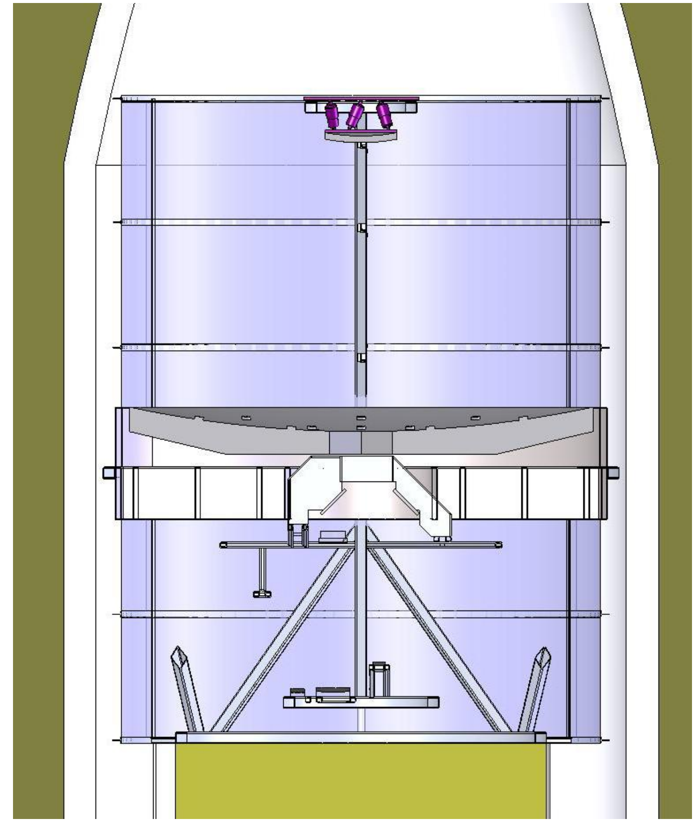
Notional surveillance instrument
Very large and well-suited to LEO

f/18 Telescope Strawman Design
Simultaneous MWIR & Visible Push Broom
1.2° x 0.04° FOV



EELV Packaging for Launch





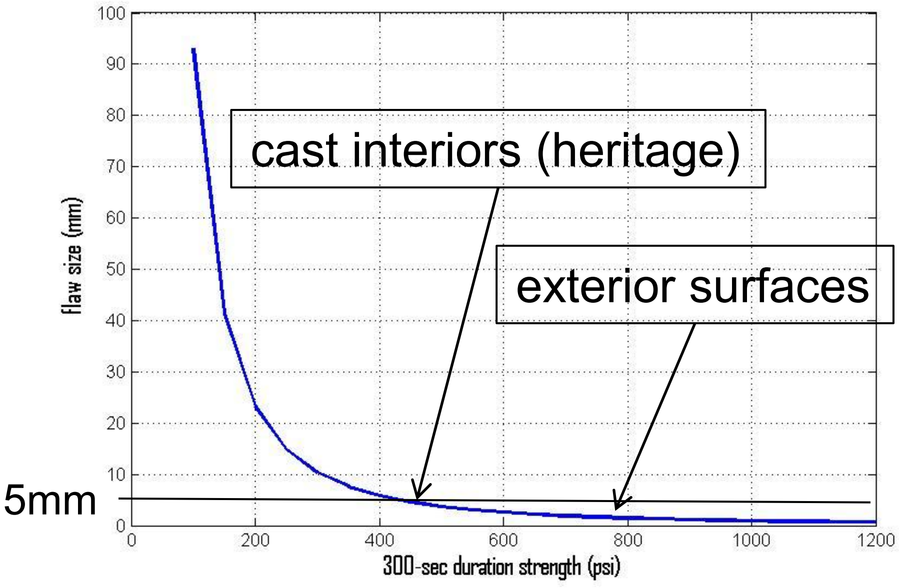
Crossection of telescope and instrument . Volume is within shroud keep-out zone.

CBE Mass Table

- Mass with pre-Phase A margin shows ~0.5 mT remaining capacity
  - No light-weighting measures have been applied except for primary mirror
  - Many details have not been included except as placeholders

P/L element	Unit Mass (lbs)	mT (metric tons) Unit mass (mT)	Quantity	Mass (CBE)	Margin	Current estimate	Basis	Note
Spacecraft (LMC)	20,000	9.091	1	9.09	10%	10.00	LMC 5/6/08	
Telescope								
Model								
18889 4M Primary Monolithic Mirror	2,500	1.136	1	1.14	30%	1.48	UASO model 6/4/08	Light-weighted E6
Monolith Secondary Mirror	90	0.041	1	0.04	30%	0.05	UASO model 6/4/08	ULE solid
18891 4M Space Telescope Cell	2,500	1.136	1	1.14	30%	1.48	UASO model 6/4/08	Steel
Rectangular Mirror One	110	0.050	1	0.05	30%	0.07	UASO model 6/4/08	ULE solid
Mirror Assembly Frame	3,700	1.682	1	1.68	30%	2.19	UASO model 6/4/08	Steel
Rectangular Mirror Two	20	0.009	1	0.01	30%	0.01	UASO model 6/4/08	ULE solid
Rectangular Mirror Four	12	0.005	1	0.01	30%	0.01	UASO model 6/4/08	ULE solid
Rectangular Mirror Five	20	0.009	1	0.01	30%	0.01	UASO model 6/4/08	ULE solid
Rectangular Mirror Three	20	0.009	1	0.01	30%	0.01	UASO model 6/4/08	ULE solid
Rectangular Mirror Six	28	0.013	1	0.01	30%	0.02	UASO model 6/4/08	ULE solid
Rectangular Filter	30	0.014	1	0.01	30%	0.02	UASO model 6/4/08	
Pps Assemblies	90	0.041	1	0.04	30%	0.05	UASO model 6/4/08	
Sleeve	1,300	0.591	1	0.59	30%	0.77	UASO model 6/4/08	Aluminum on steel frame
Monolith Lid	800	0.364	1	0.36	30%	0.47	UASO model 6/4/08	
Hexapod	200	0.091	1	0.09	30%	0.12	UASO model 6/4/08	
Other elements								
Hardpoints	22	0.010	6	0.06	30%	0.08	Guess	
Primary mirror actuators	11	0.005	50	0.25	30%	0.33	Guess	
WCSS	440	0.200	1	0.20	30%	0.26	Guess	
Secondary								
Secondary cell	90	0.041	1	0.04	30%	0.05	Guess to equal SM	
Wavefront monitoring system								
Hartmann mirror system	1	0.001	36	0.02	30%	0.02	Guess	
Shack-Hartmann at ISS	22	0.010	1	0.01	30%	0.01	Guess	
Focal plane detector	1,320	0.600	1	0.60	30%	0.78	Guess	
Thermal management								
Blankets	176	0.080	1	0.08	30%	0.10	need placeholder	
Deployments					30%		need placeholder	
Active system	220	0.100	1	0.10	30%	0.13	need placeholder	
Telescope control electronics								
Power supply	11	0.005	1	0.01	30%	0.01	SWAG	
Thermal monitoring	2	0.001	1	0.00	30%	0.00	SWAG	
Computer	11	0.005	1	0.01	30%	0.01	SWAG	
Interfaces								
Mechanical interface	44	0.020	1	0.02	30%	0.03	Guess	
Cables	110	0.050		0.05	30%	0.07	Guess	
Launch restraints	110	0.050		0.05	30%	0.07	Guess	
			Total	**15.77**	**18%**	**18.69**		
						19.20	**Launch capacity**	
			3.43	22%	**3%**	**0.51**	**Net & reserve**	

Launch Survival of Primary: As-Cast E6 Flaws Affect Strength



- 300-sec duration strength (3σ) vs. flaw size in E6 as-cast. The 99% strength is 450 psi for 5mm flaw size. Further blank structure optimization and localized interior grinding will create significant improvements that guarantee launch and flight testing with ample margin.
- Exterior surfaces finished to 0.2mm flaws using standard procedures

Current UASO casting procedures detect and repair all flaws down to 5mm (450 psi).

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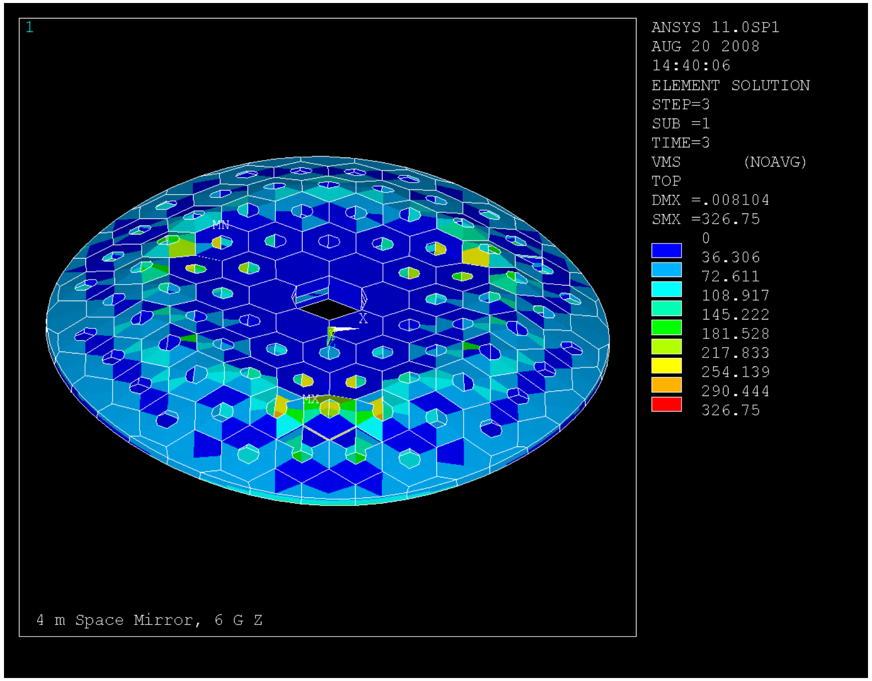
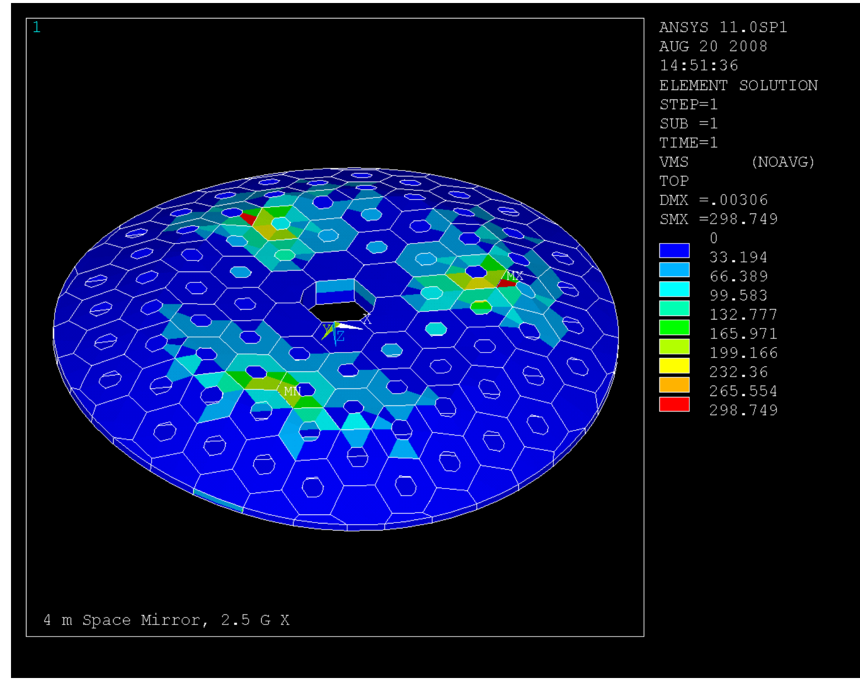
3-Point Support Stresses





Three-point stress distributions for 6gz (left) and 2.5 gx load cases. The total area of stress near 300 psi is small and can be further reduced through design. Bipod will have 6-pt contact, so survival has even more margin.

Analysis shows current UASO casting processes survive 3-point launch loads.

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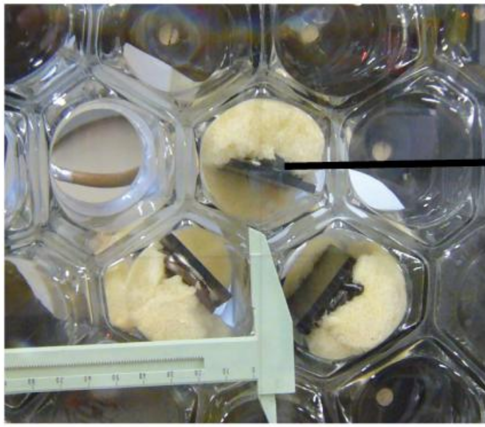
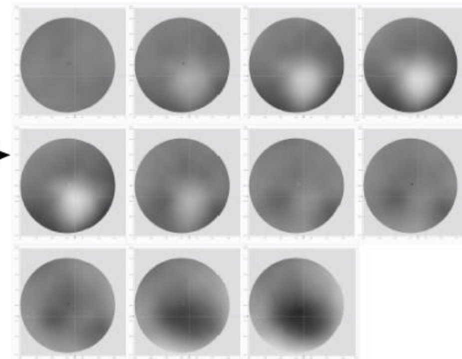
Using the glass CTE to advantage by thermal figuring the primary mirror

Angel, Kang, Cuerden, Guyon, Stahl; SPIE 2007

One-cell demonstration on 18" OD, 60mm thick E6 Hextek mirror



Detail of honeycomb mirror cells with cooling fingers inserted through hole in the back plate, seen through the face plate.



Metrology of 145 mm diameter region covering one thermally controlled cell of a borosilicate mirror. The surface figure is shown by gray scale from -130 nm (black) to + 150 nm (white). The actuator maximum corresponds to 200 mW heating of three adjacent ribs,

Previous work has shown that complete thermal figuring should be possible. Such figuring turns the borosilicate CTE into an advantage and could eliminate the need for instruments to provide a wavefront correction relay.

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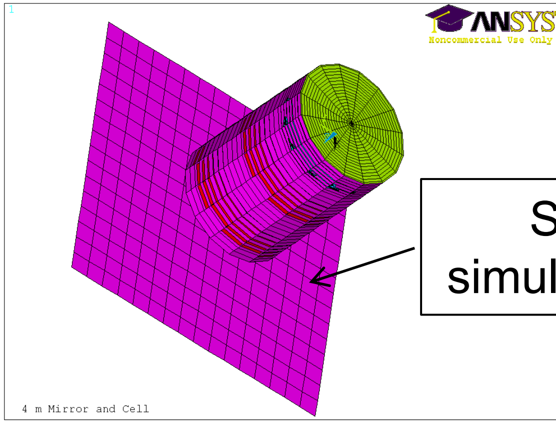
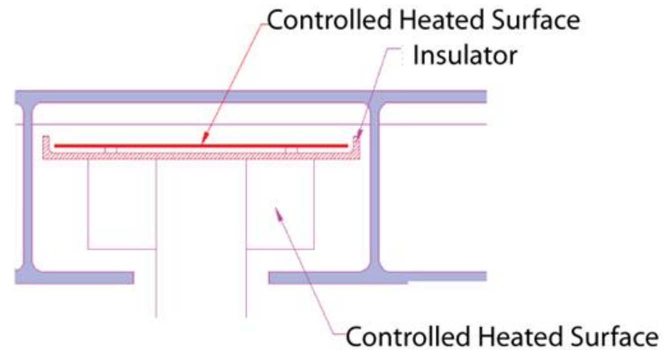
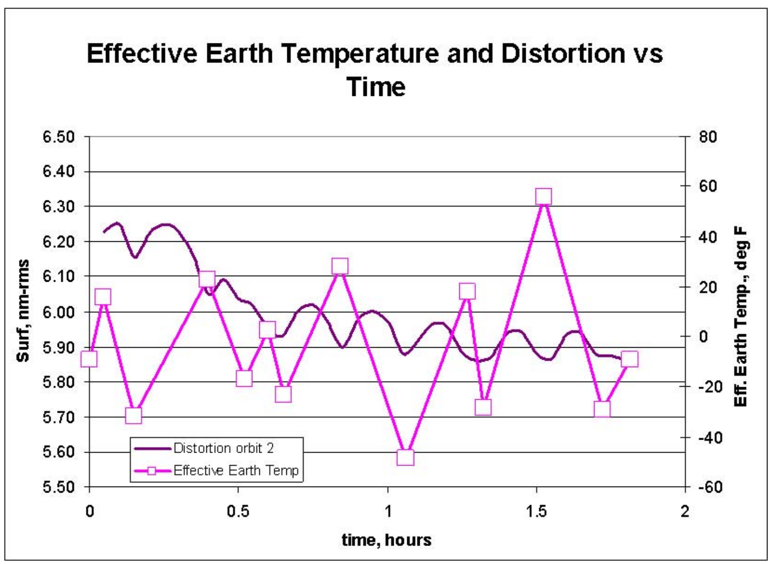
Thermal Figuring: Earth Looking with a sun-lit 290K thermal shroud

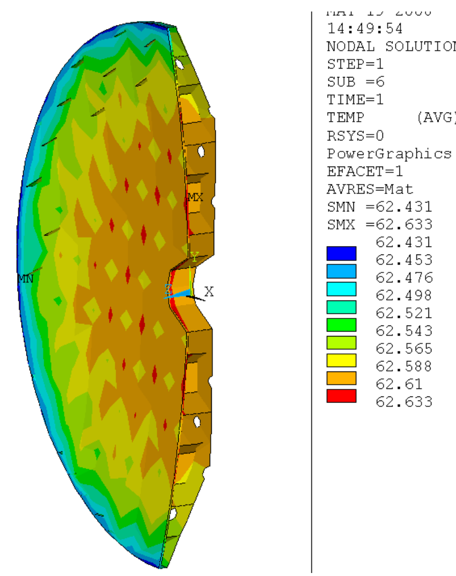


Surface simulates Earth

Each mirror cell contains a radiative heater with 2 zones







0.1 C P-V

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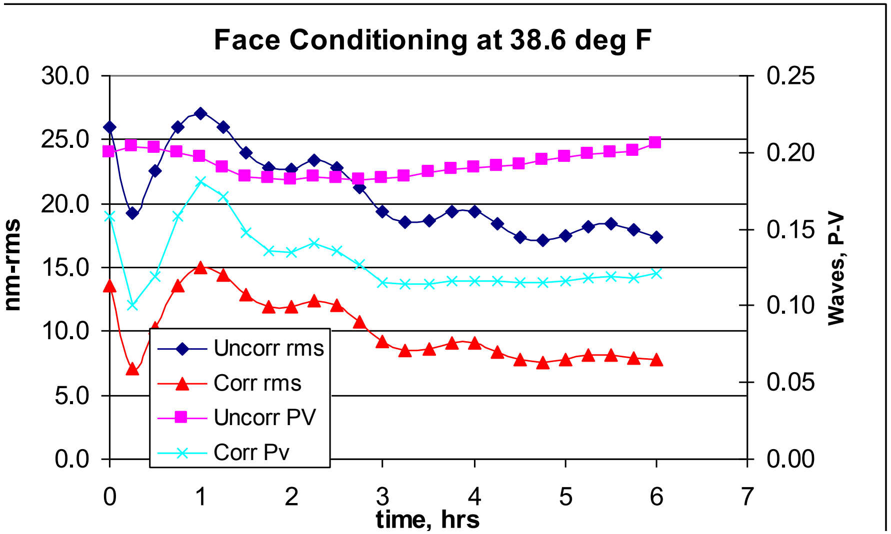
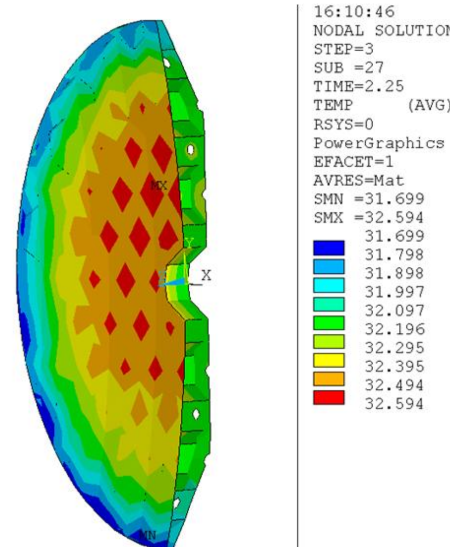
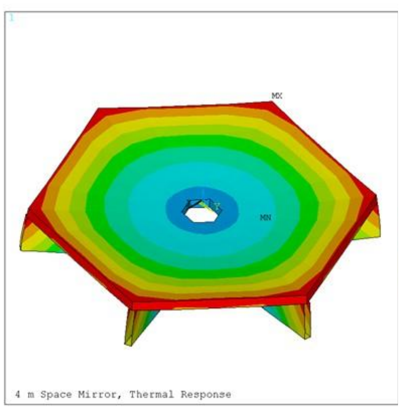
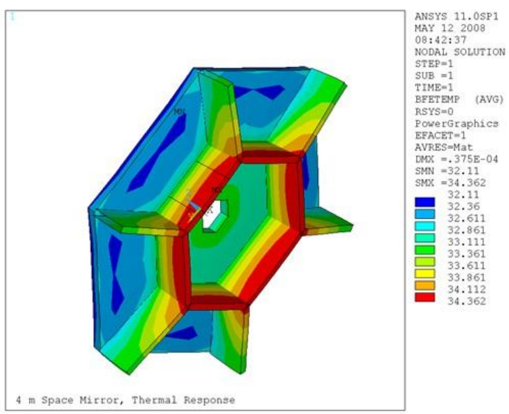
Thermal Figuring: Space-Looking with a sun-lit 270K thermal shroud





0.4C P-V



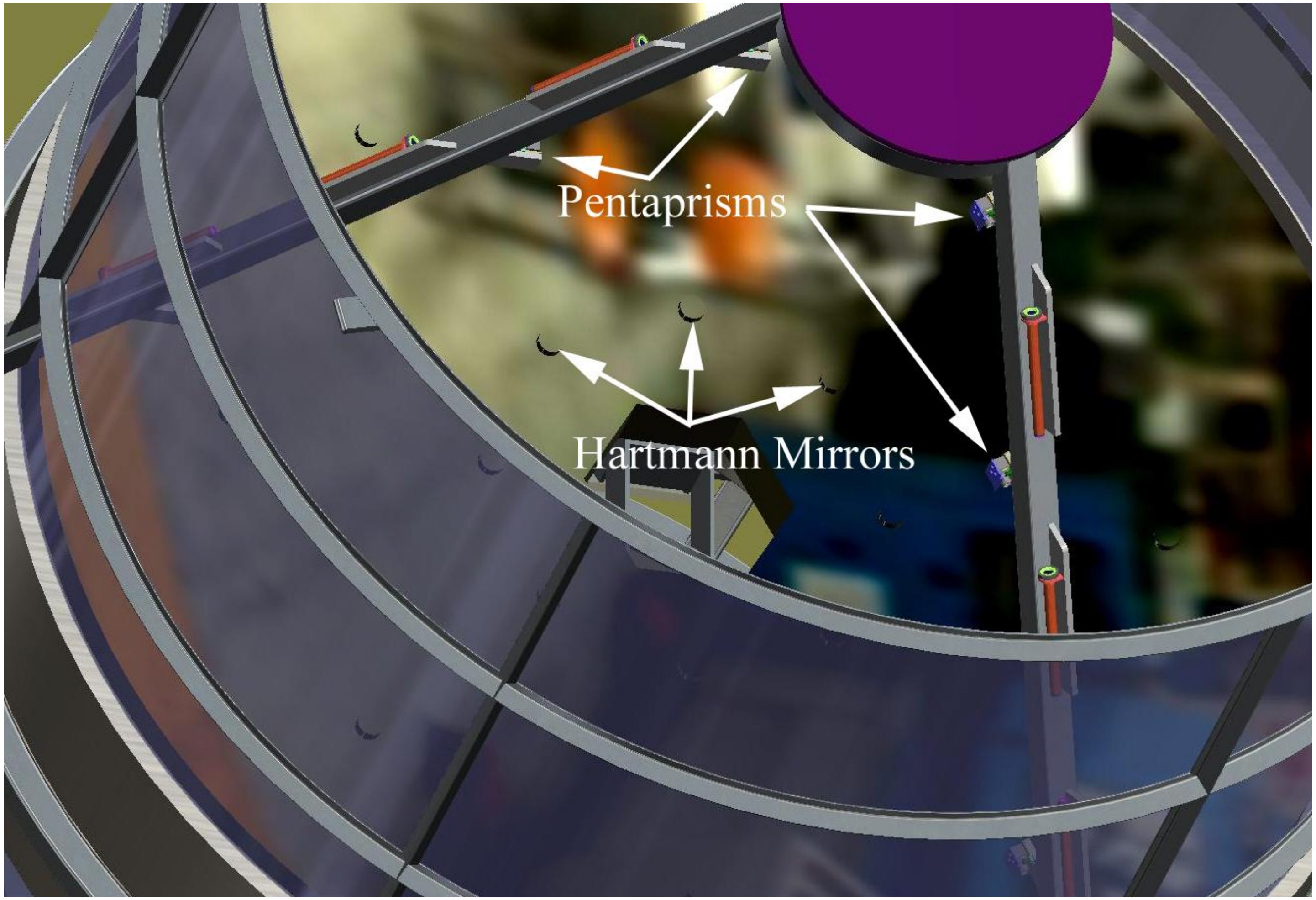


← Thermal error distribution of each mirror cell might require another thermal zone to eliminate for space-looking.

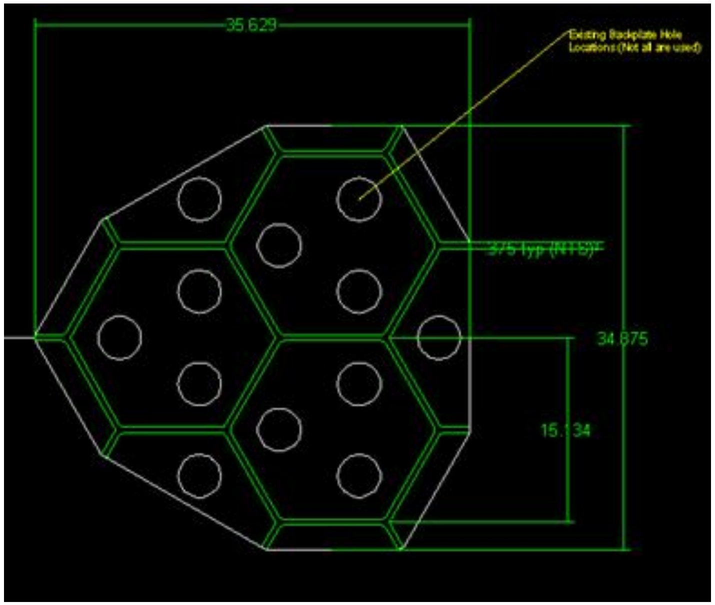
Thermal conditioning conclusions

- **Demonstrated good performance for earth-looking case including scene temperature changes and sun exposure with fixed set points so good figure is assured once the set points are established for the average conditions.**
- **Space-looking performance is not yet demonstrated for a high-quality UV telescope (further analysis is needed).**
- **Heater set points appear to have a tolerance of 0.05 C which is an achievable level, particularly since they only have to be maintained to within that range once the set point is established.**
- **Additional temperature controlled zones can be added to further improve performance.**
- **Total thermal conditioning power estimates:**
  - **An e^* = 0.008 shroud loses 350W to space, but gains 380W from solar heating, so balancing is needed (maybe via heat pipes)**
  - **When scene is 10C cooler than shroud, 30W is required increasing to 300W for space-looking.**
  - **80W is required to equalize earth-shadow cases**
  - **Total power estimates: earth-looking ~ 110W, space-looking ~ 500W**

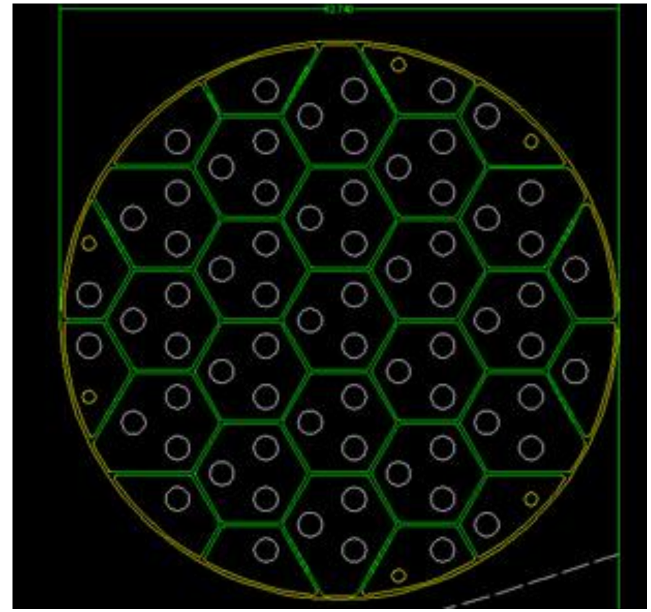
Flight WFC Implementation
on-orbit wavefront insurance policy



Upcoming work: casting mirrors with 95 kg/m^2 areal density



3-cell castings in small furnace for strength samples



2m diameter castings for TRL demonstrations of launch survival loads

Upcoming work: thermal figuring

We have a 1.8m mirror with a high quality sphere polished into it that will be used to test complete thermal mirror figuring.

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Conclusions

- E6 borosilicate has been shown to be a credible primary mirror substrate material for space imaging applications.
- It's particularly well suited for earth-looking where the scene and shroud temperatures can be matched.
- Producing a high-quality space-looking telescope however requires more work to identify better thermal management schemes.
- The relatively high CTE of borosilicate has the potential to create thermal figuring solutions free of moving parts and relieving instruments of wavefront correction duties.
- Analysis shows high potential for cast structures to survive launch environment with good factors.
- Borosilicate is the only glass that can be cast in complex shapes. It has the potential to create cost-effective, low risk monolithic space imagers whose technology has already been proven at Ares V shroud diameters.